Moving Closer to a Detection of nHz-frequency Gravitational Waves with

(and an ode to Arecibo)

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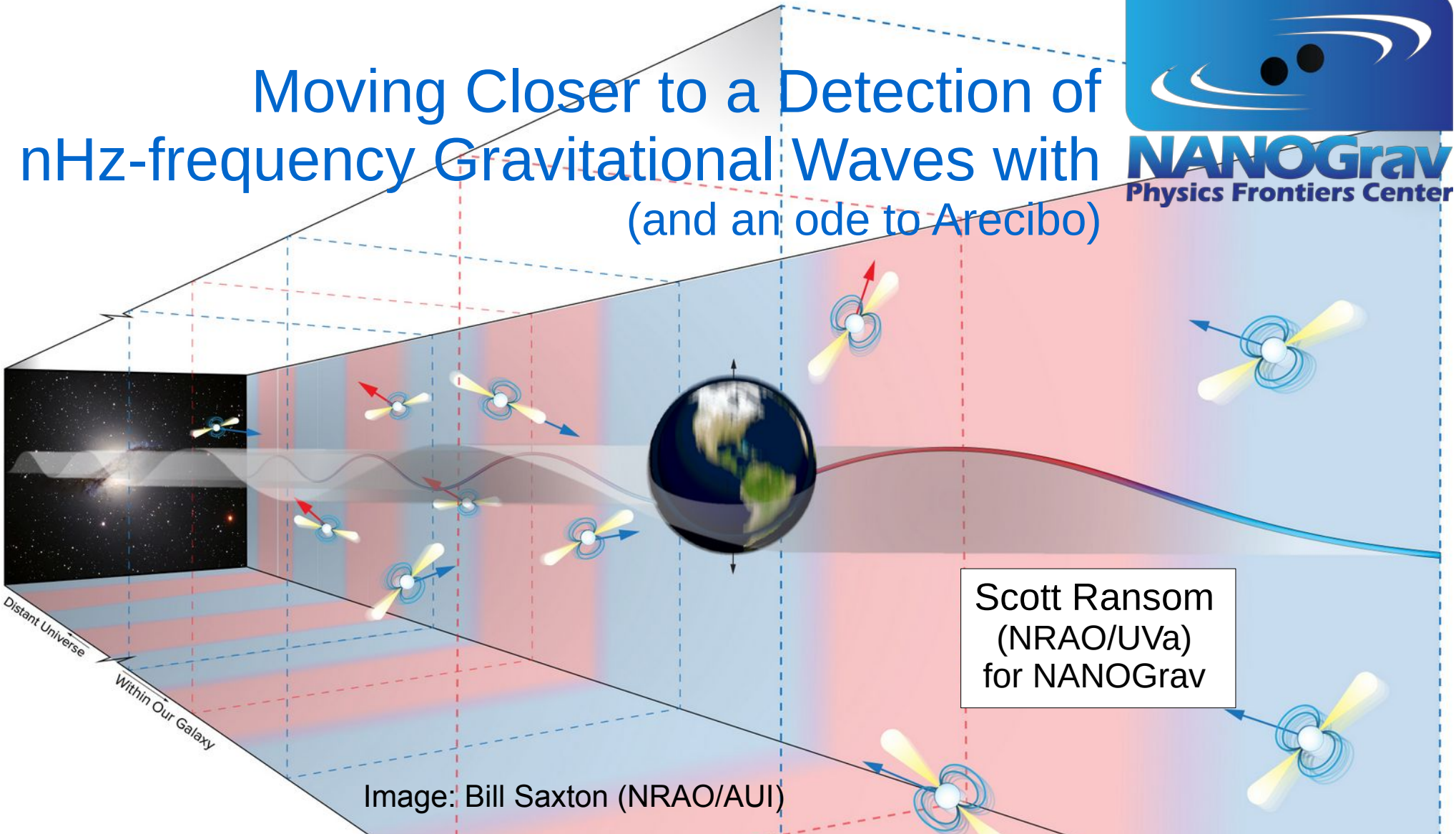


Scott Ransom
(NRAO/UVa)
for NANOGrav

Image: Bill Saxton (NRAO/AUI)

North American Nanohertz Observatory for GWs

NANOGrav Physics Frontiers Center

http://nanograv.org/

Our mission is to detect nHz frequency gravitational waves from super-massive black hole binaries.

We are over 100 students and scientists and welcome new collaborators and members.

Astro2020 Project White Paper

The NANOGrav Program for Gravitational Waves and Fundamental Physics

The North American Nanohertz Observatory for Gravitational Waves

July 10, 2019

Thematic areas: Multi-messenger astronomy and astrophysics; Cosmology and fundamental physics; Formation and evolution of compact objects.

Contact author: Scott Ransom (NANOGrav Chair), NRAO, scott.ransom@nanograv.org

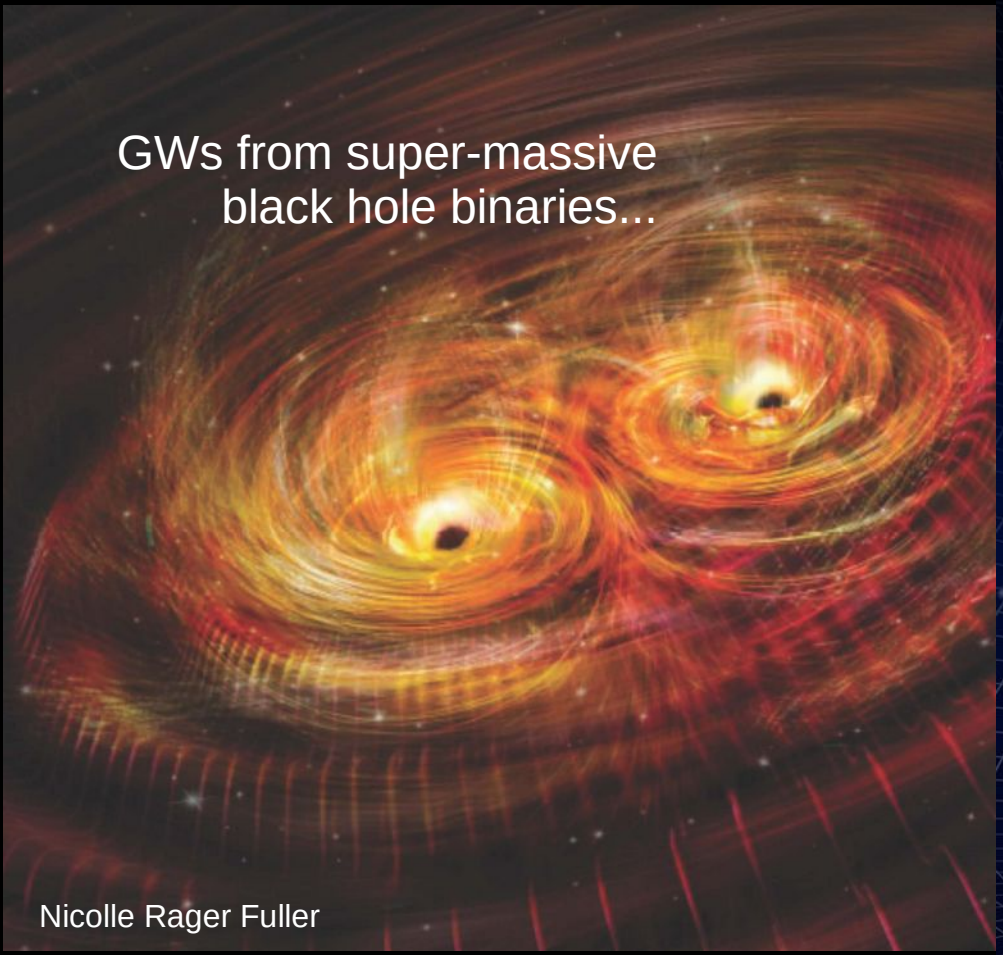
Authors: A. Brazier (Cornell), S. Chatterjee (Cornell), T. Cohen (NMT), J. M. Cordes (Cornell), M. E. DeCesar (Lafayette), P. B. Demorest (NRAO), J. S. Hazboun (UW Bothell), M. T. Lam (WVU, RIT), R. S. Lynch (GBO), M. A. McLaughlin (WVU), S. M. Ransom (NRAO), X. Siemens (OSU, UWM), S. R. Taylor (Caltech/JPL, Vanderbilt), and S. J. Vigeland (UWM) for the NANOGrav Collaboration ($\sim$ 50 institutions, 100+ individuals)

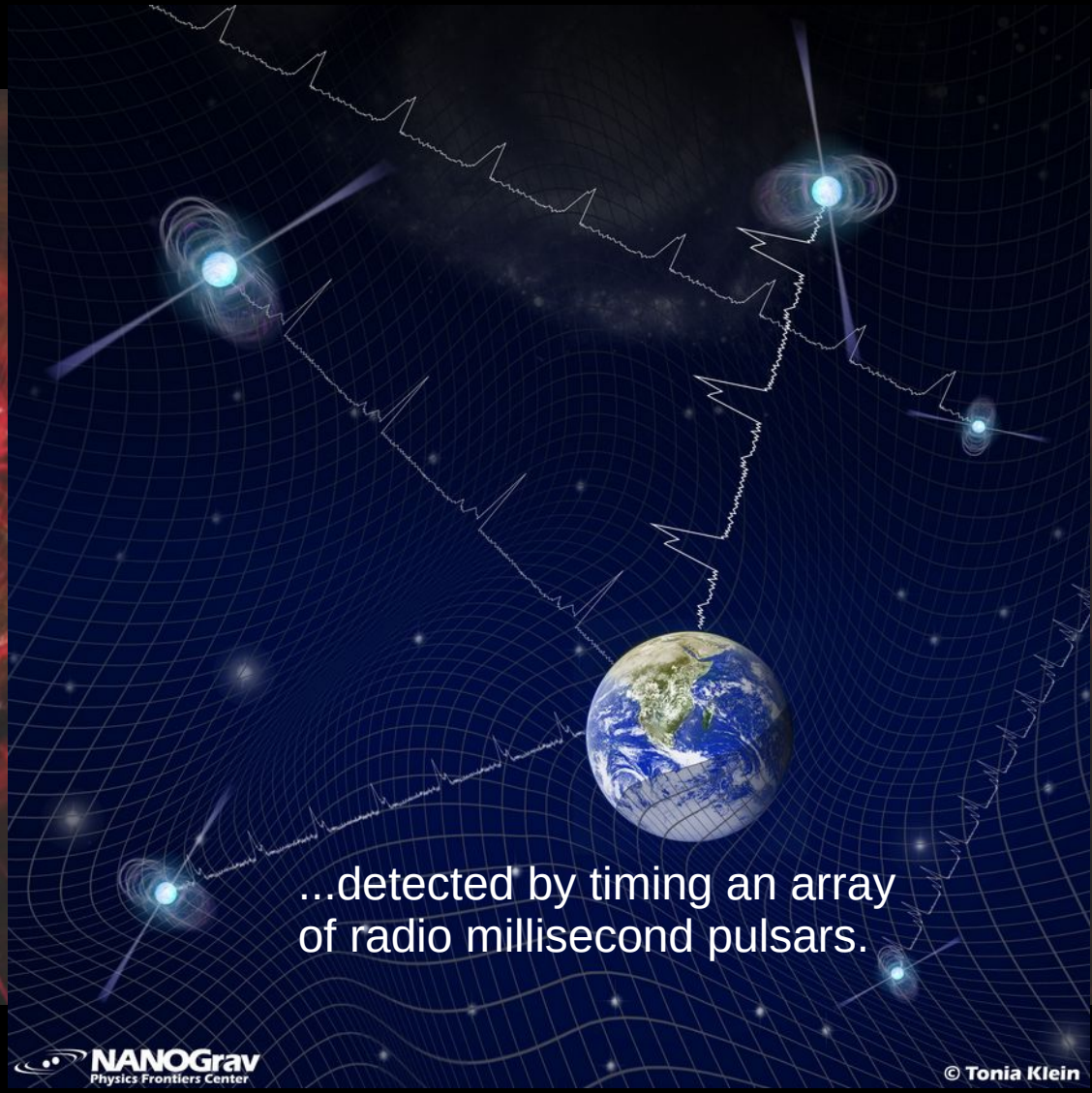
Ransom et al. 2019, Astro2020 Whitepaper

But not just NANOGrav...

Parkes Pulsar
Timing Array

European Pulsar
Timing Array


GWs from super-massive
black hole binaries...
Nicolle Rager Fuller


...detected by timing an array
of radio millisecond pulsars.
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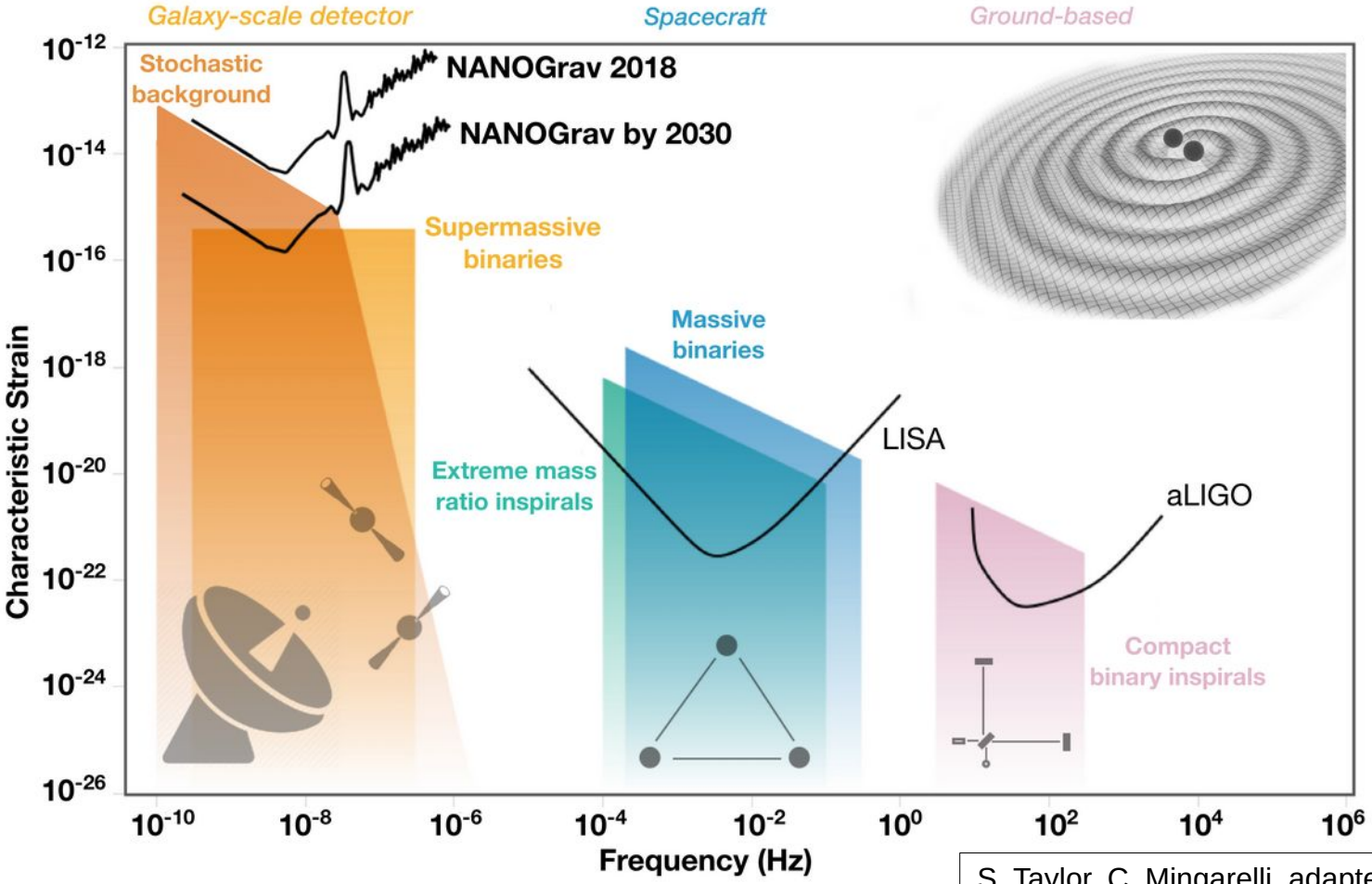
The Gravitational Wave Spectrum

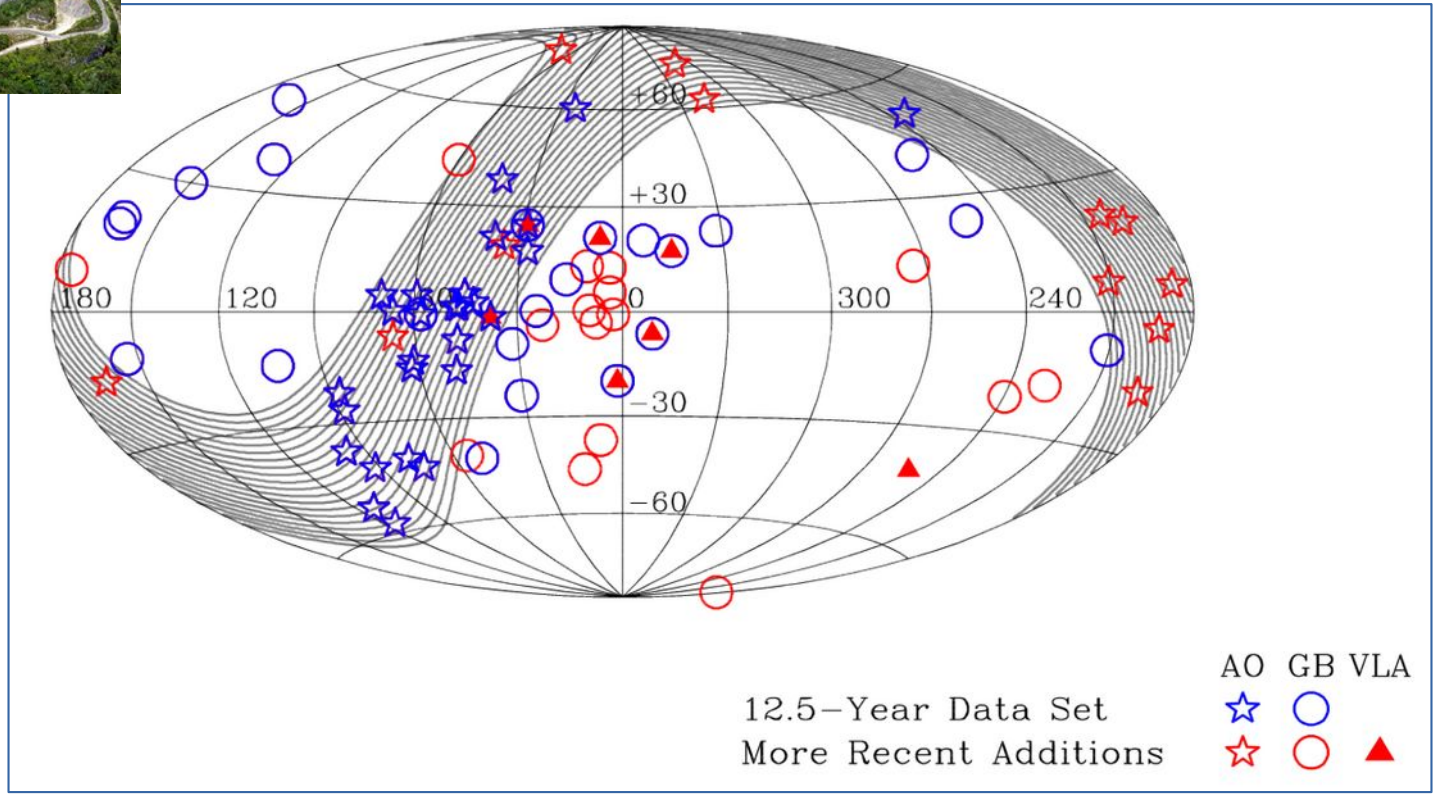


S. Taylor, C. Mingarelli, adapted from gwplotter.org (Moore, Cole, Berry 2014)

Both Arecibo and the GBT are Crucial

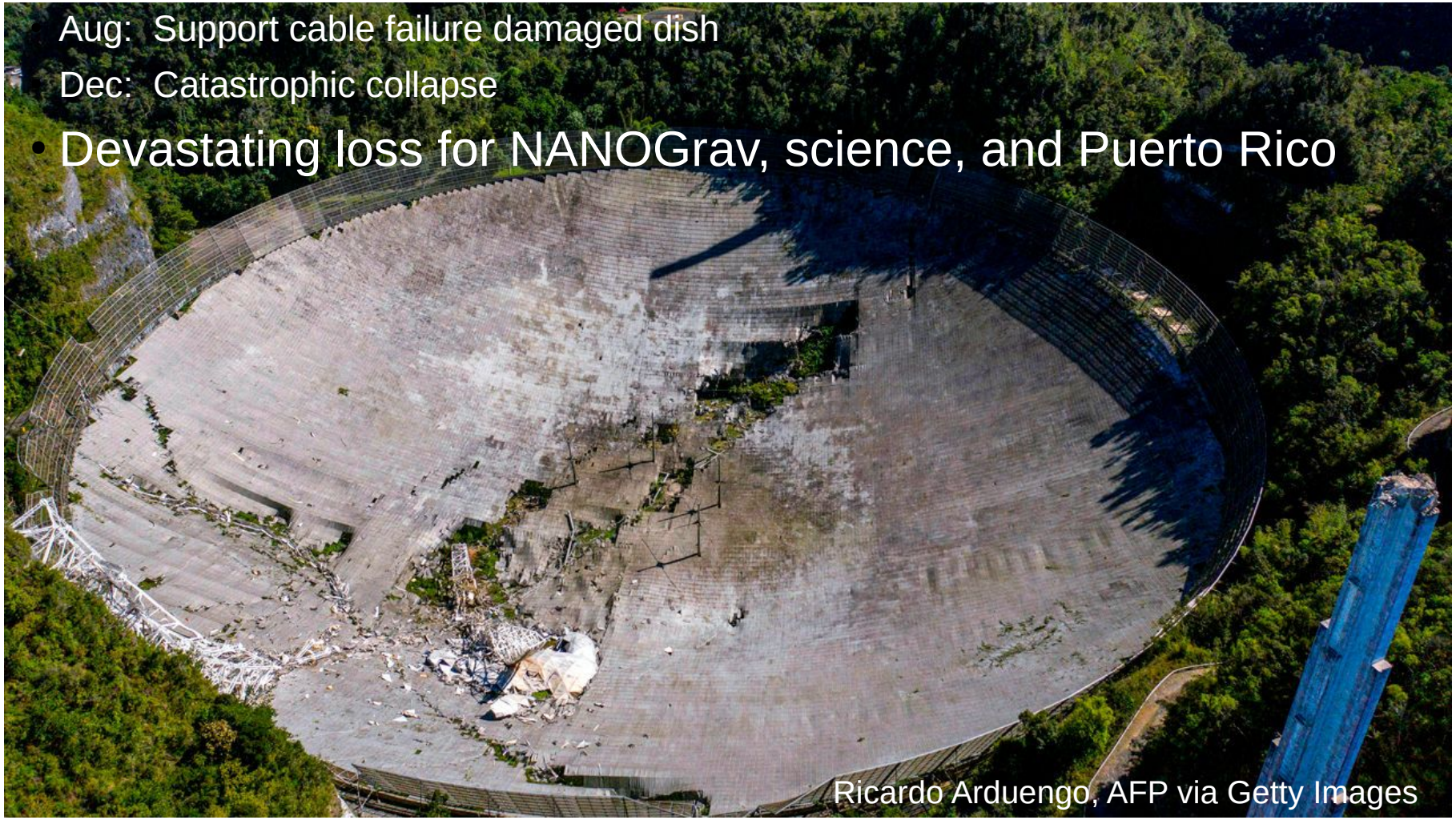
Each telescope provides ~50% of our GW sensitivity

- **Arecibo** has 4-5x sensitivity
- **GBT** has 3x sky coverage



Loss of Arecibo

- Aug: Support cable failure damaged dish
- Dec: Catastrophic collapse
- Devastating loss for NANOGrav, science, and Puerto Rico



Ricardo Arduengo, AFP via Getty Images

Arecibo's Pulsar Legacy

1968 Crab spin period (Lovelace et al)

1970 pulsar nulling (Backer)

1974 1st binary pulsar (Hulse & Taylor)

1982 1st millisecond pulsar (Backer et al)

1989 indirect GWs from B1913+16 (Taylor & Weisberg)

1990 1st eclipsing MSP (aka black-widow; Fruchter et al)

1992 pulsar planets (1st exoplanets!; Wolszczan & Frail)

1994 microsec long-term timing (Kaspi, Ryba, & Taylor)

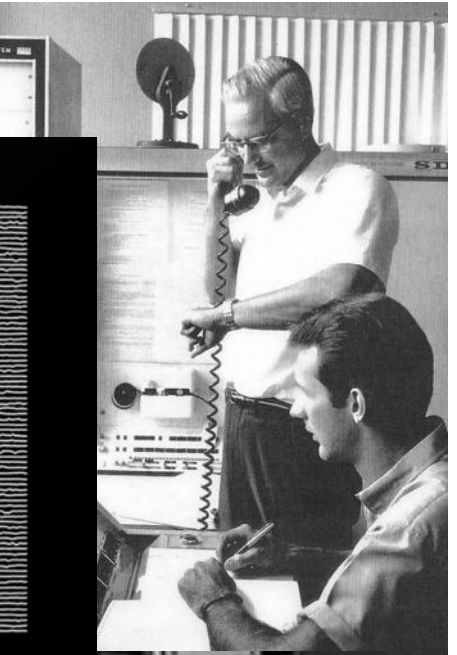
2008 an MSP in an eccentric orbit (Champion et al)

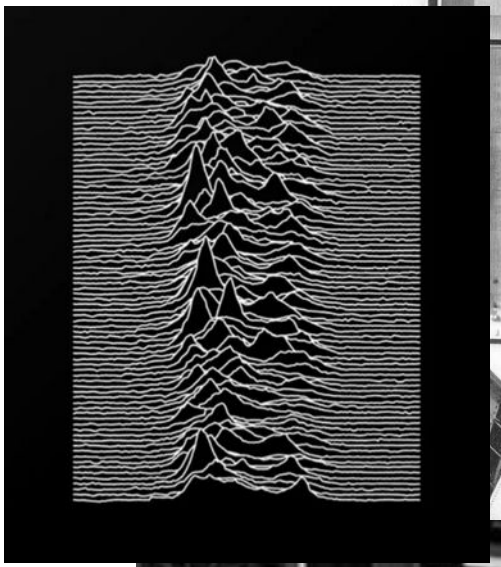
2014 1st non-Parkes FRB (Spitler et al)

2016 1st FRB repeater (Spitler et al)

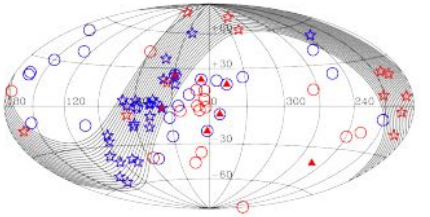
2018 SEP test with triple system (Archibald et al)

… and much much more (plus non-pulsar science!)





NANOGrav Observing Program



Arecibo Observatory

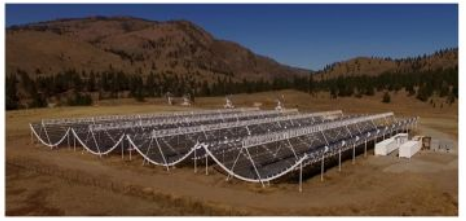
- Main program: 39 pulsars / dual receiver / every three weeks (began 2004)
- High cadence program: 5 pulsars / dual receiver / every week (began 2015)

Green Bank Telescope

- Main program: 39 pulsars / dual receiver / every month (began 2004)
- High cadence program: 2 pulsars / single receiver /every week (began 2014)

Very Large Array

- Experimental program: 7 pulsars / single or dual receiver
- Sensitive 2-4 GHz system expands frequency coverage
- Can see slightly further south than GBT (1 pulsar)

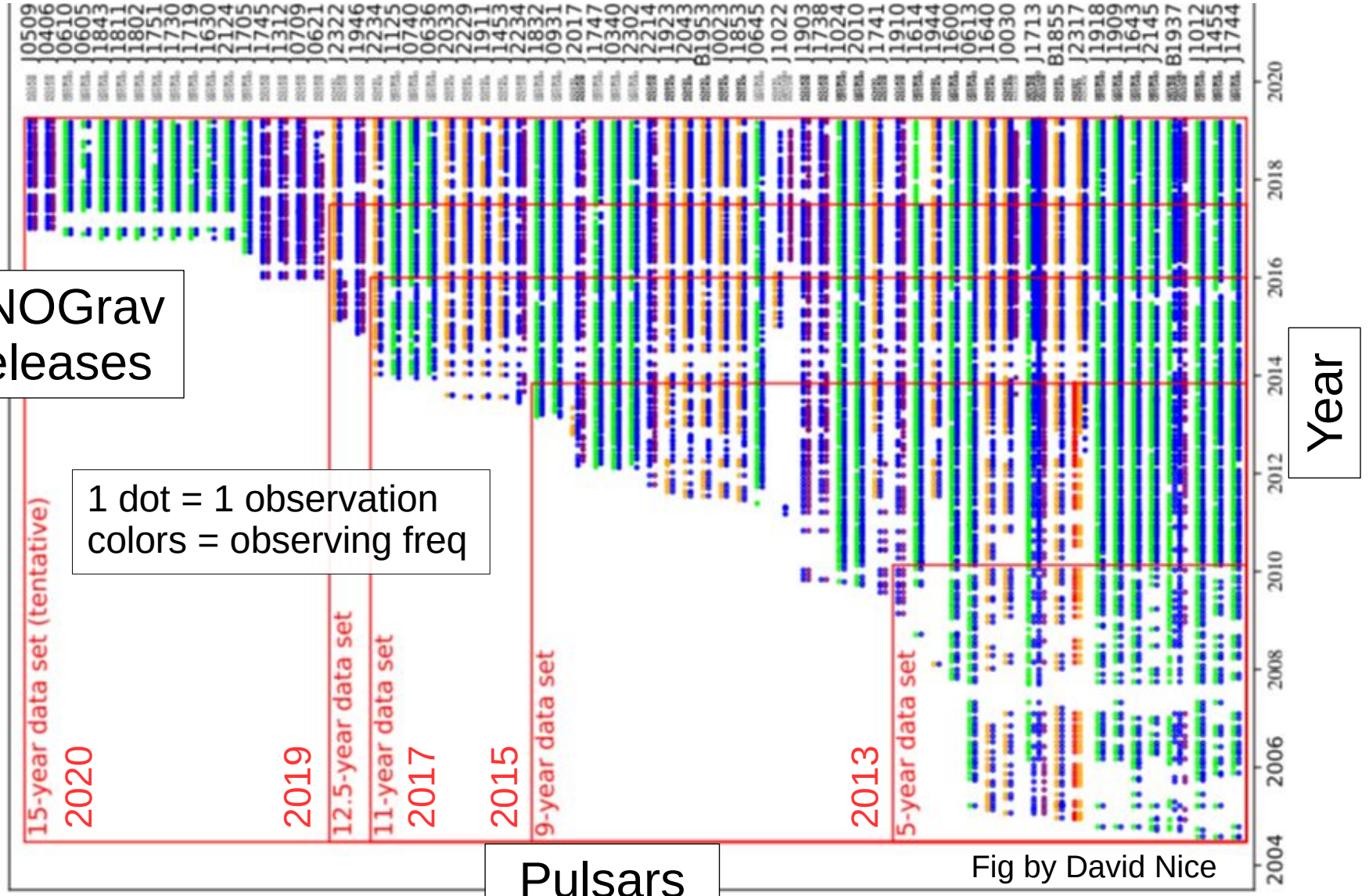


CHIME (with CHIME/Pulsar collaboration)

- 400 to 800 MHz
- All NANOGrav pulsars at $\delta \gtrsim -20^\circ$ observed daily (!)
- Dwell time ~5 min/cos(δ) (began late 2018)
- Still in engineering phase; challenging to calibrate

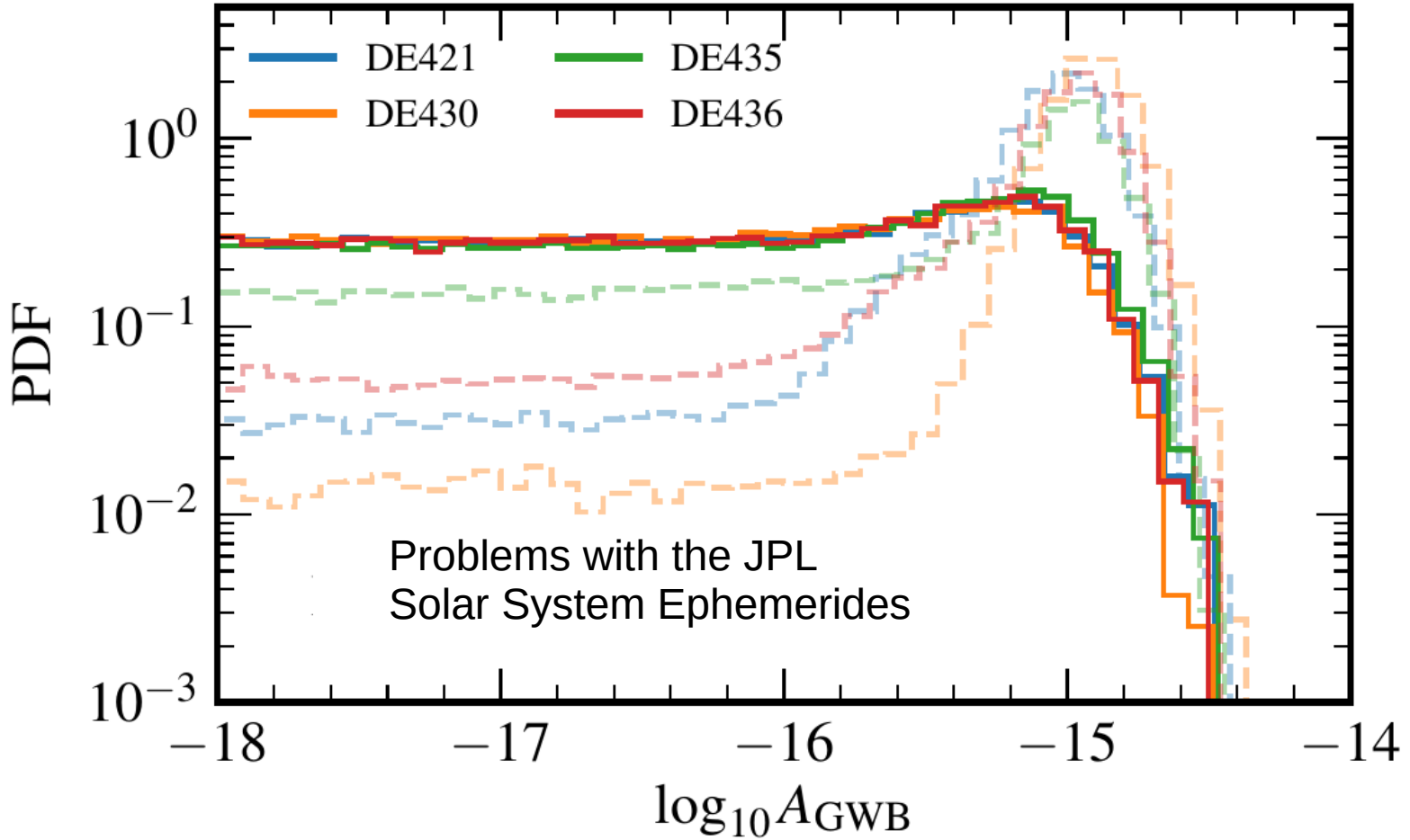
Slide by David Nice

The NANOGrav Data Releases



1 dot = 1 observation
colors = observing freq

NANOGrav 11 Year GW Bkgd Results



Arzoumanian et al., 2018, ApJ, 859, 47

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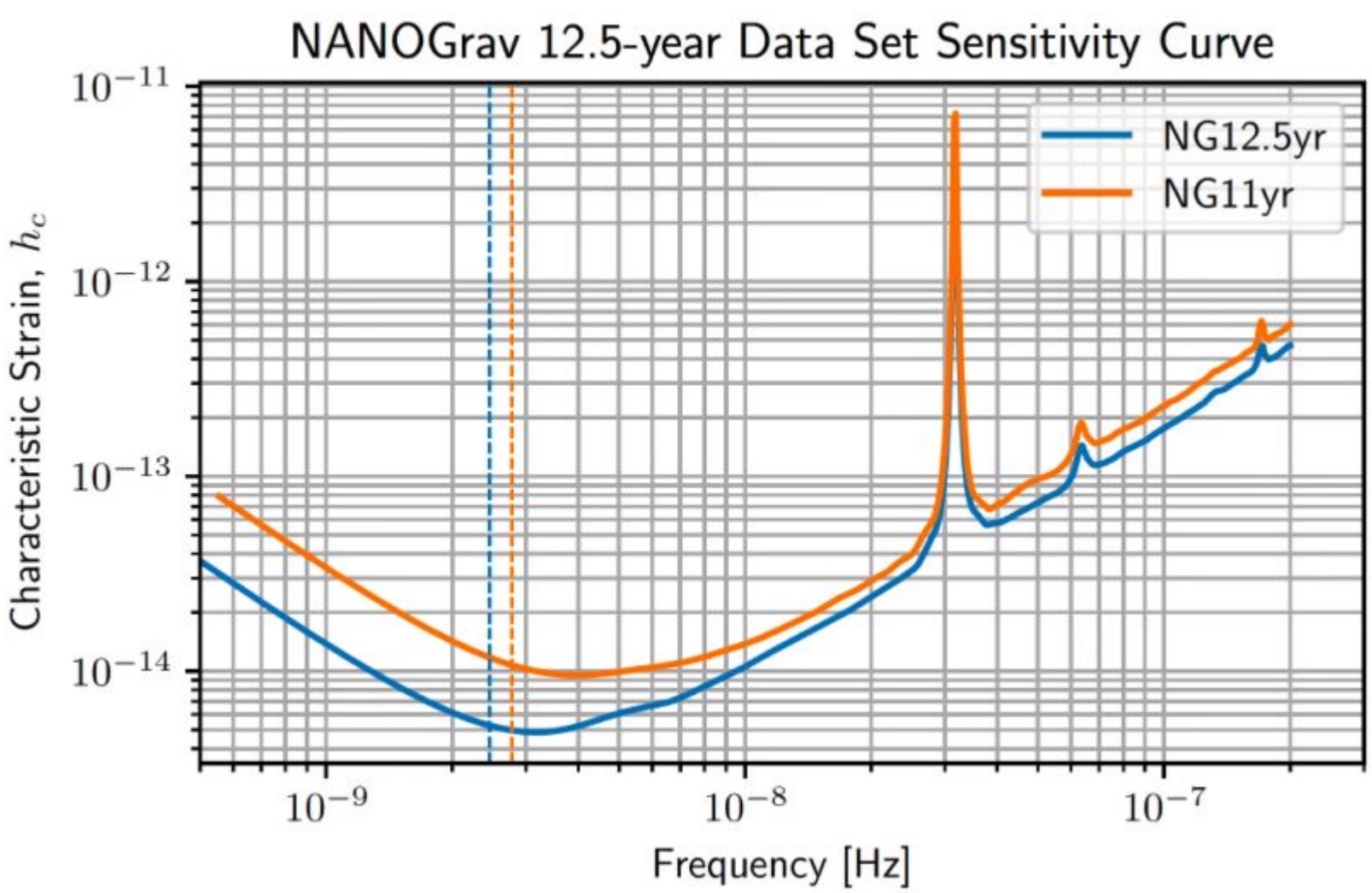

Hazboun, Romano, & Smith, 2019, PhRvD

NSF

AO

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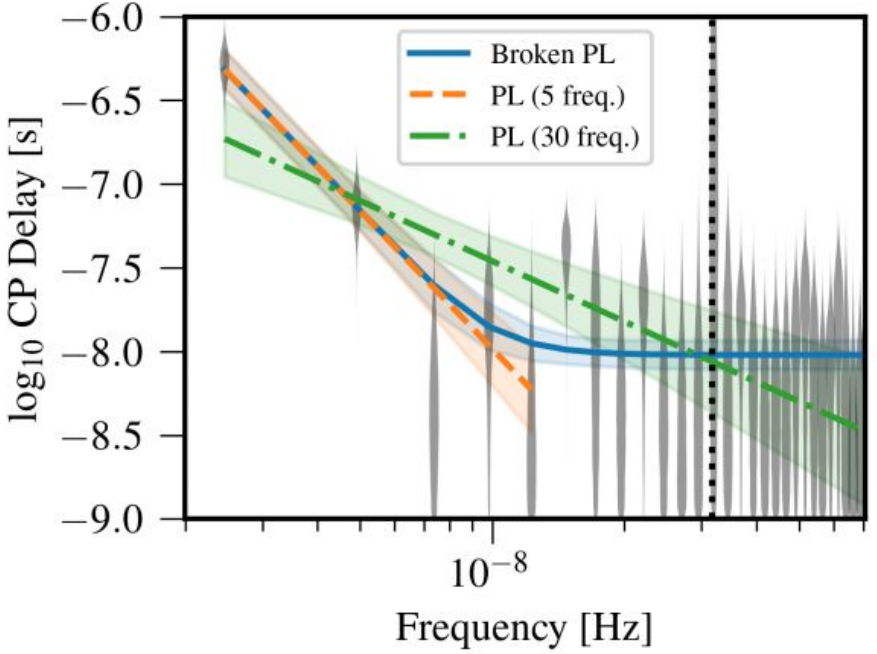
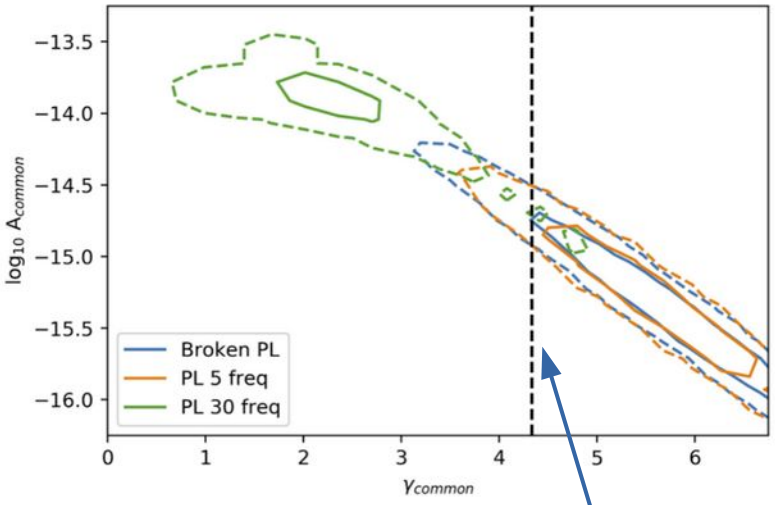
12.5 Year Bkgd Results

Seeing significant low-freq noise in the data….



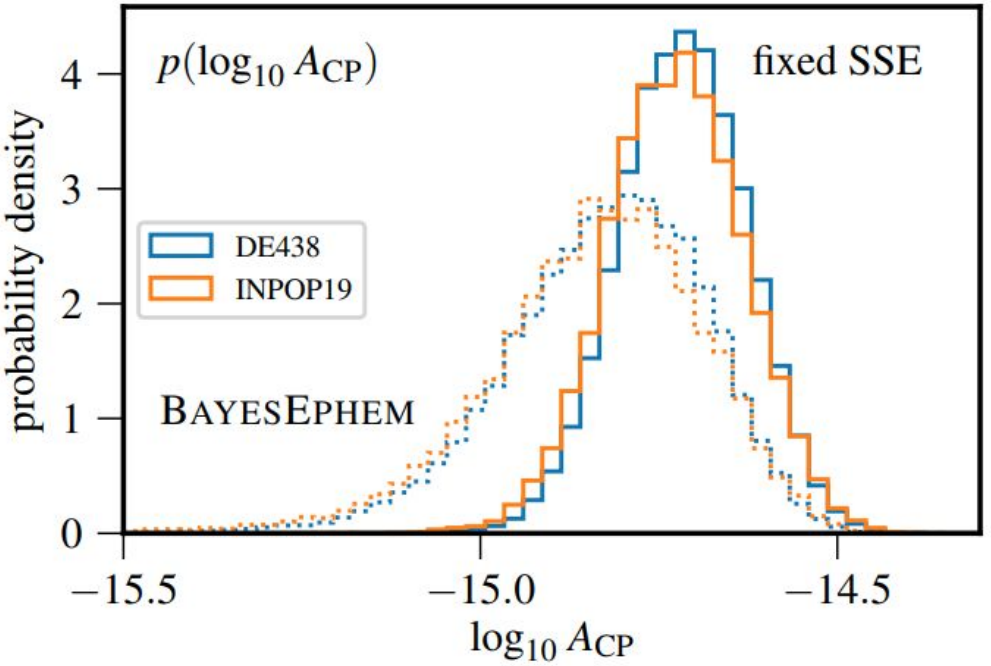
Figures courtesy Joe Simon;
Arzoumanian et al. 2020, ApJL, arXiv:2009.04496



Expected spectral index for a GWB from inspiraling SMBHBs (**γ**=13/3)

12.5 Year Bkgd Results

Strong evidence for ***uncorrelated*** **common red noise process**…
(Bayes factors of ~30,000:1 in favor for fixed SS Ephem)

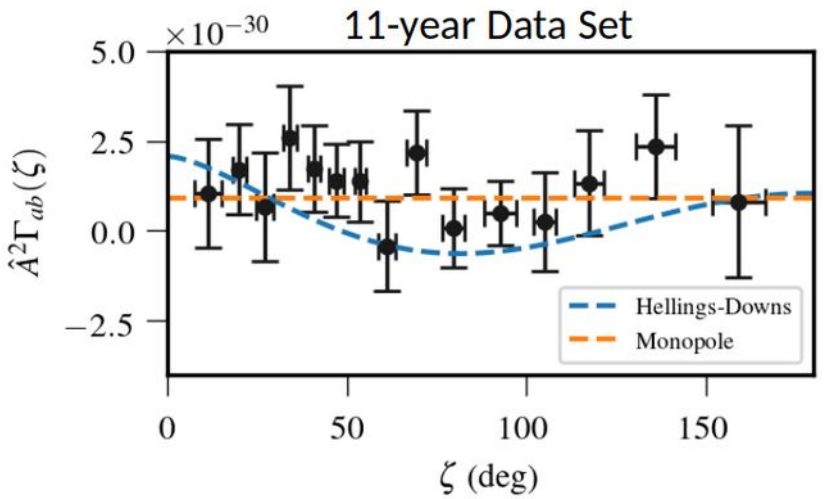


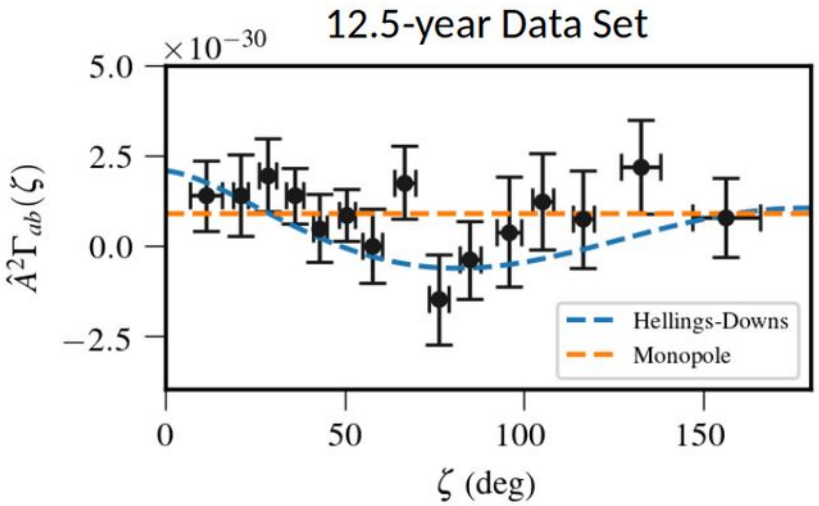
Figures courtesy Joe Simon;
Arzoumanian et al. 2020, ApJL, arXiv:2009.04496

12.5 Year Bkgd Results

No good evidence of the required *spatial correlations* yet…

But the data are improving rapidly,
and there are ~2+ more years of data in the bank!





Figures courtesy Joe Simon;
Arzoumanian et al. 2020, ApJL, arXiv:2009.04496

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1. arXiv:2010.04018 [pdf, other] astro-ph.GA
A direct constraint on the Galactic acceleration and the Oort limit from pulsar timing
Authors: Sukanya Chakrabarti, Philip Chang, Michael T. Lam, Sarah J. Vigeland, Alice C. Quillen
Submitted 8 October, 2020; originally announced October 2020.
Comments: submitted to ApJ Letters

2. arXiv:2010.03976 [pdf, other] astro-ph.CO gr-qc hep-th
NANOGrav Hints on Planet-Mass Primordial Black Hol
Authors: Guillem Domènech, Shi Pi
Submitted 8 October, 2020; originally announced October 2020.
Comments: 7 pages, 3 figures
Report number: IPMU20-0106

3. arXiv:2010.02189 [pdf, other] astro-ph.CO astro-ph.GA hep-ph
Testing Stochastic Gravitational Wave Signals from Pr
Authors: Sunao Sugiyama, Volodymyr Takhistov, Edoardo Vitagliano,
Submitted 5 October, 2020; originally announced October 2020.
Comments: 5 pages, 1 figure
Report number: IPMU20-0105

4. arXiv:2009.14663 [pdf, other] astro-ph.CO gr-qc hep-th
Is the NANOGrav signal a hint of dS decay during infla
Authors: Hao-Hao Li, Gen Ye, Yun-Song Piao
Submitted 30 September, 2020; originally announced September 2020.
Comments: 9 pages,2 figures

5. arXiv:2009.14174 [pdf, other] astro-ph.CO astro-ph.HE
NANOGrav signal from MHD turbulence at QCD phase
Authors: A. Neronov, A. Roper Pol, C. Caprini, D. Semikoz
Submitted 29 September, 2020; originally announced September 2020.
Comments: 5 pages, 2 figures

6. arXiv:2009.13909 [pdf, other] astro-ph.CO gr-qc hep-ph
Implications of Gravitational-wave Production from D
Number of Relativistic Species
Authors: Ryo Namba, Motoo Suzuki
Submitted 5 October, 2020; v1 submitted 29 September, 2020; originally announ
Comments: 13 pages, 2 figures. Minor changes, citation additions

7. arXiv:2009.13893 [pdf, other] astro-ph.CO hep-ph
NanoGrav 12.5-yr data and different stochastic Gravit
Authors: Ligong Bian, Jing Liu, Ruiyu Zhou
Submitted 29 September, 2020; originally announced September 2020.
Comments: 18 pages, 5 figures, 1 table; comments welcome

8. arXiv:2009.13452 [pdf, other] hep-ph astro-ph.CO astro-ph.GA
Gravitational wave complementarity and impact of N
Authors: Rome Samanta, Satyabrata Datta
Submitted 30 September, 2020; v1 submitted 28 September, 2020; originally ann
Comments: 16 pages, 4 figures, typo corrected, refs. updated

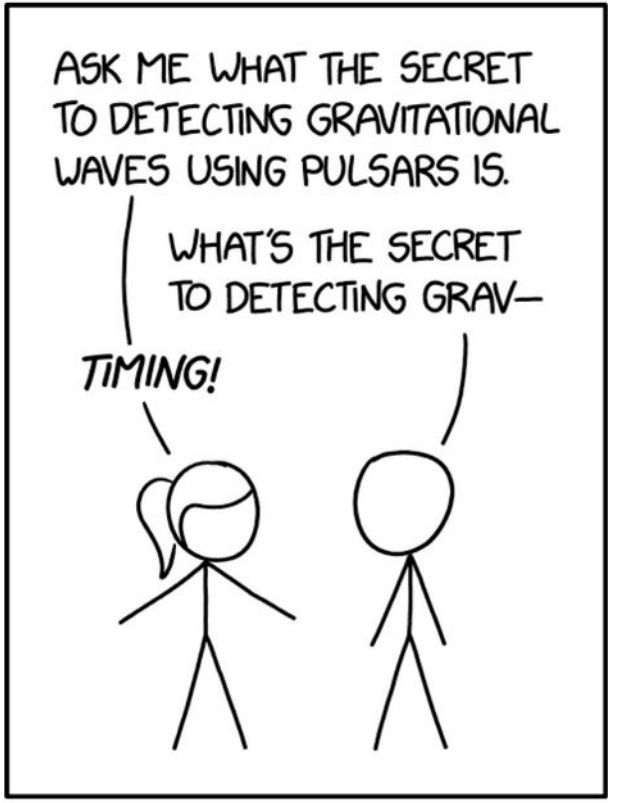
9. arXiv:2009.13432 [pdf, other] astro-ph.CO gr-qc hep-ph
Implications of the NANOGrav pulsar timing results fo
Authors: Sunny Vagnozzi
Submitted 28 September, 2020; originally announced September 2020.
Comments: 7 pages, 2 figures. Short spoiler: no, NANOGrav is very unlikely to be

10. arXiv:2009.11875 [pdf, other] astro-ph.CO hep-ph
Whispers from the dark side: Confronting light new p
Authors: Wolfram Ratzinger, Pedro Schwaller
Submitted 24 September, 2020; originally announced September 2020.
Comments: 10 pages, 5 figures
Report number: MITP/20-056

11. arXiv:2009.11865 [pdf, other] astro-ph.GA gr-qc
Multimessenger pulsar timing array constraints on supermassive black hole binaries traced by periodic light curves
Authors: Chengcheng Xin, Chiara M. F. Mingarelli, Jeffrey S. Hazboun
Submitted 24 September, 2020; originally announced September 2020.
Comments: 11 pages, 4 figures, submitted to ApJ

GRAVITATIONAL WAVE PULSARS

< PREV RANDOM NEXT >



12. arXiv:2009.11853 [pdf, other] astro-ph.CO gr-qc hep-ph hep-th
Solar-Mass Primordial Black Holes Explain NANOGrav Hint of Gravitational Waves
Authors: Kazunori Kohri, Takahiro Terada
...2020; originally announced September 2020.
...g the title change)
...PTC-20-22

hep-ph
...table cosmic strings
...Kai Schmitz
...eptember 2020.

...der Phase Transitions
...Antonino Marciano, Kaiqiang Zeng
...mber, 2020; originally announced September 2020.
...nspired GW spectra added, including more recent numerical tools in the subject. New references added. The main conclusions

gr-qc hep-ph
...ion from Dark Phase Transition: Connecting NANOGrav Pulsar Timing Data and
...ou Takahashi, Masaki Yamada
...mber, 2020; originally announced September 2020.
...r the sound-wave period included, figures updated, conclusions unchanged

...servations to Monitor Dispersion with the Giant Metrewave Radio Telescope
...Jayanta Roy, Michael T. Lam, James M. Cordes, David L. Kaplan, Bhaswati Bhattacharyya, Lina Levin
...eptember 2020.
...hysical Journal

gr-qc hep-ph
...Holes as Dark Matter
...eptember 2020.

...nordial black hole formation?
...mber, 2020; originally announced September 2020.

gr-qc hep-ph hep-th
...for cosmic strings?
...tz
...mber, 2020; originally announced September 2020.
...he higher cosmic-string modes [see Eq. (6)], resulting in a few numerical but no qualitative changes

astro-ph.HE gr-qc hep-ph hep-th
...OGrav Pulsar Timing Data
...mber, 2020; originally announced September 2020.
...proved accuracy of the calculation leading to a minor modification of the results

astro-ph.GA gr-qc
...earch For An Isotropic Stochastic Gravitational-Wave Background
...rsha Blumer, Bence Becsy, Adam Brazier, Paul R. Brook, Sarah Burke-Spolaor, Shami Chatterjee, Siyuan Chen,
...wford, H. Thankful Cromartie, Megan E. DeCesar, Paul B. Demorest, Timothy Dolch, Justin A. Ellis, Elizabeth C.
...han Garver-Daniels, Peter A. Gentile, Deborah C. Good, Jeffrey S. Hazboun, A. Miguel Holgado , et al. (36
...eptember 2020.
...Submitted to The Astrophysical Journal Letters

22. arXiv:2005.13549 [pdf, other] hep-ph astro-ph.CO hep-th
Gravitational waves and proton decay: complementary windows into GUTs
Authors: Stephen F. King, Silvia Pascoli, Jessica Turner, Ye-Ling Zhou

Predictions for Future

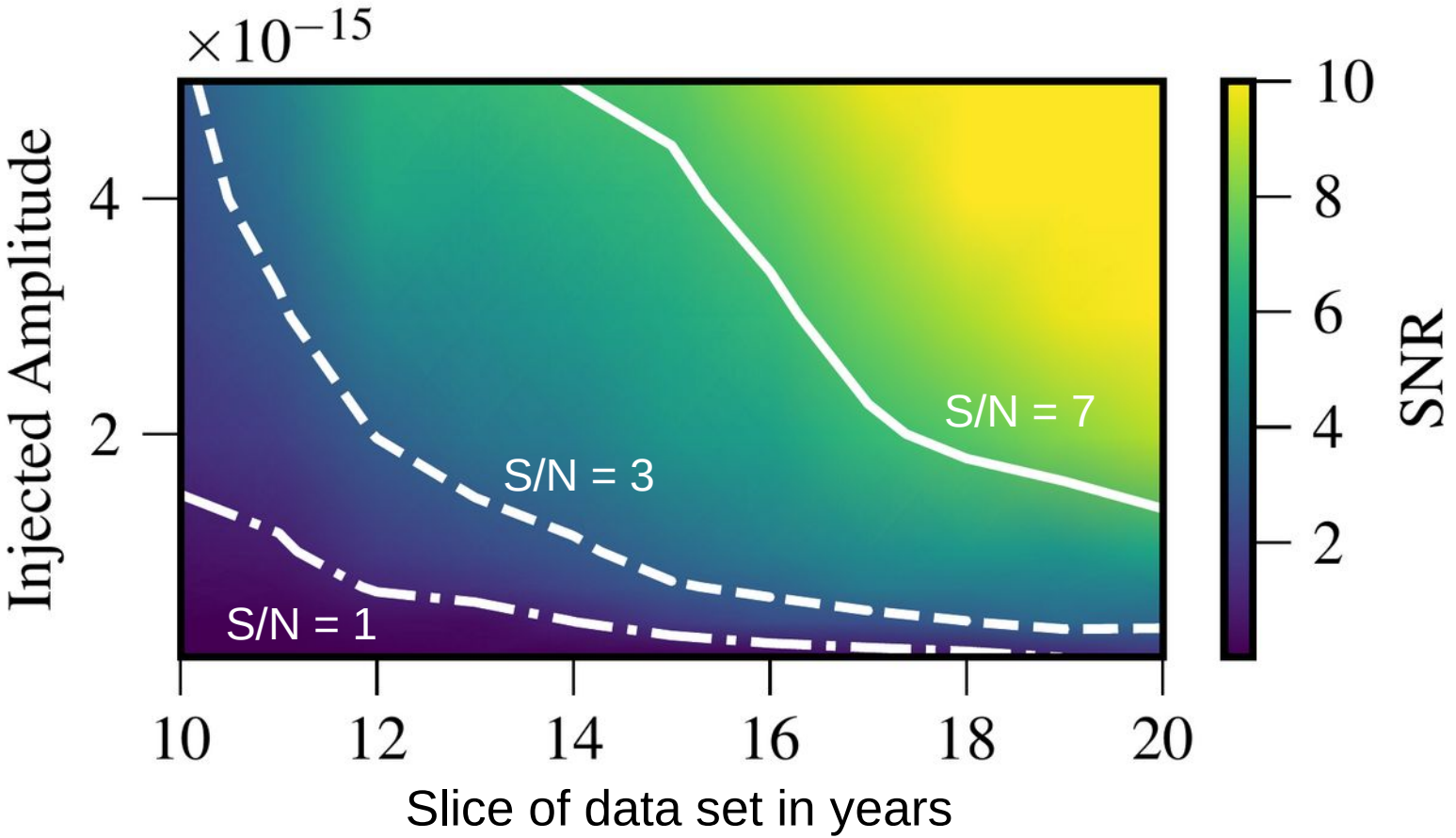


Fig courtesy of Nihan Pol (arXiv:2010.11950)

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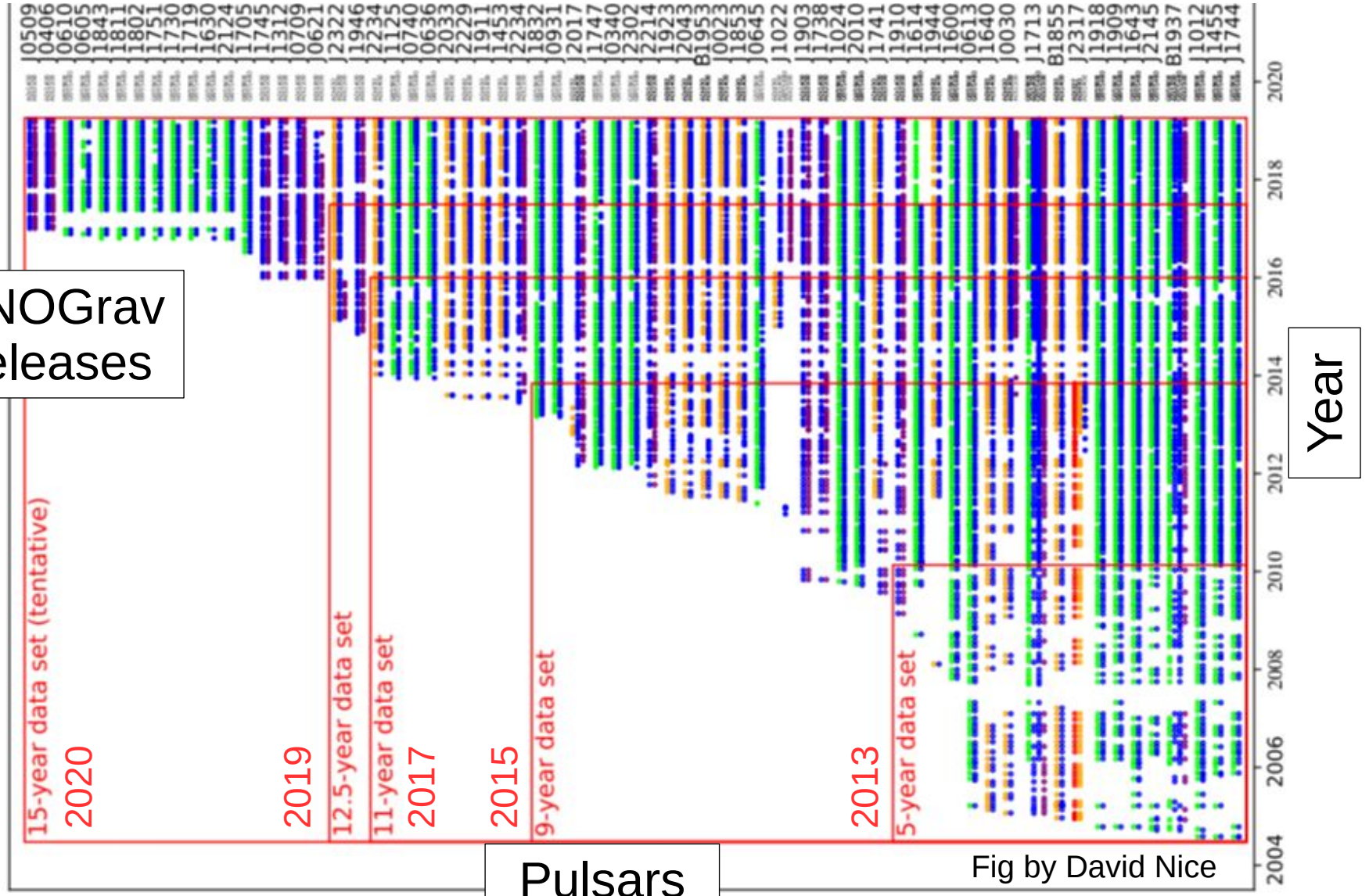
The NANOGrav Data Releases



Pulsars

Fig by David Nice

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The NANOGrav Data Releases

Gravitational wave sensitivity is proportional to the number of MSPs!

$$\propto N_{PSR} T^{1/2} \sigma^{-3/13}$$

See Siemens et al 2013 (CQG)

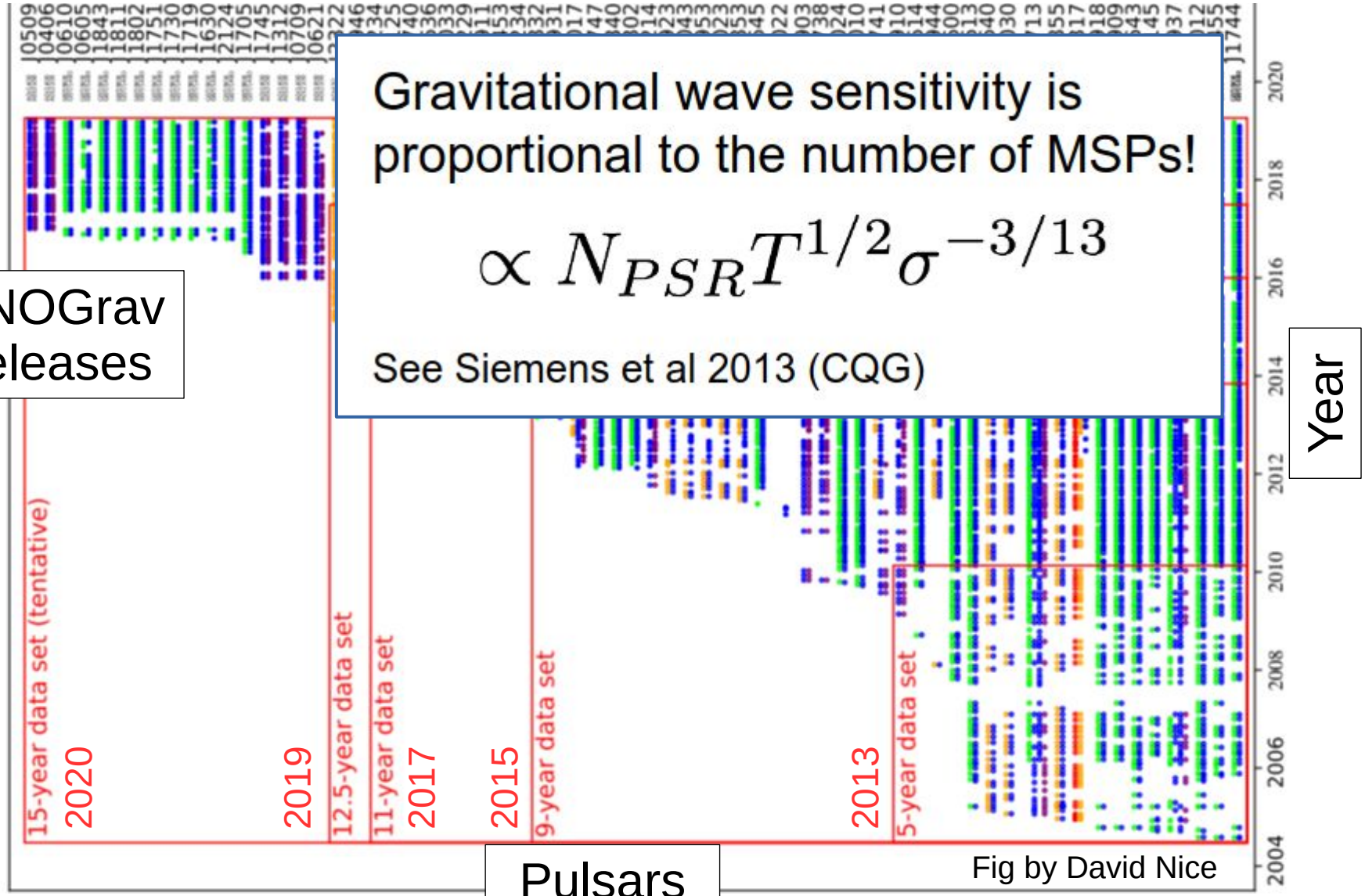

Fig by David Nice

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Predictions for Future

Predictions for future MSPs, using AO, GBT, and DSA-2000 telescopes

~200 MSPs timeable at ~1μs

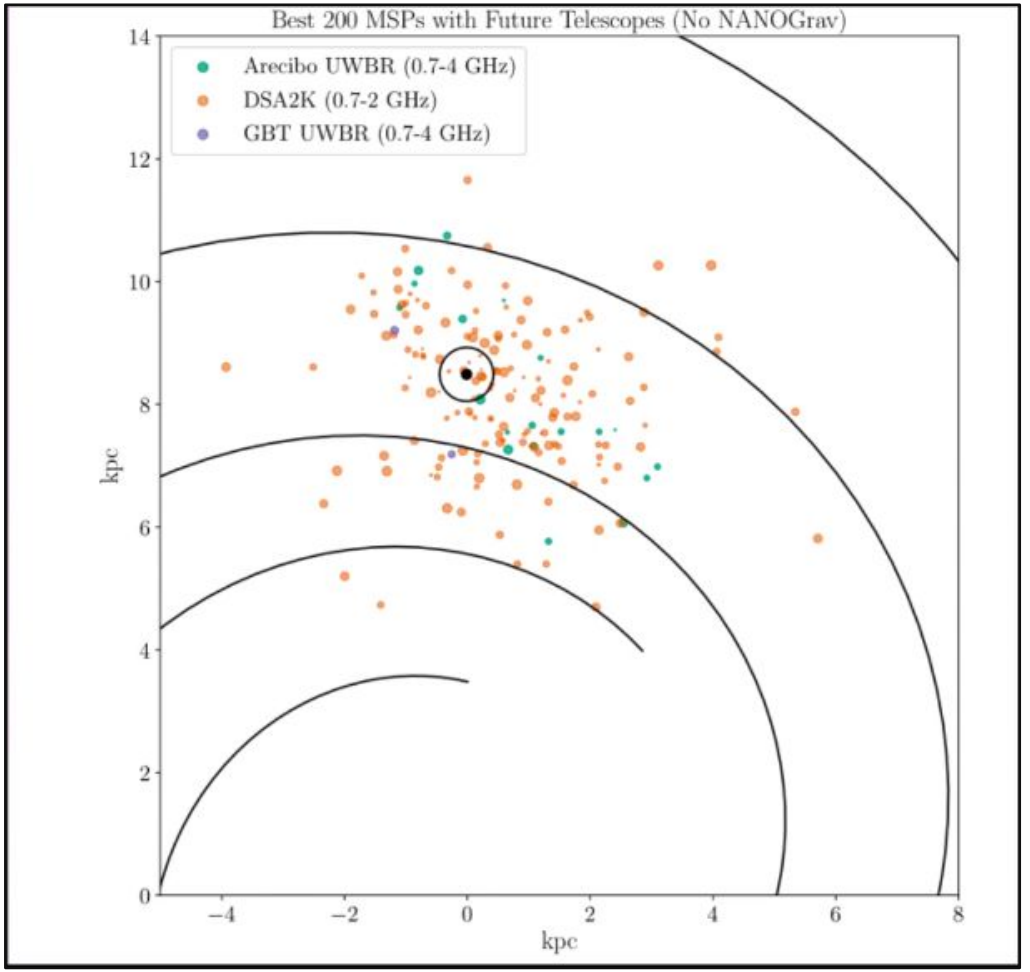


Fig courtesy of Tyler Coher and Paul Demorest

Predictions for Future

Should detect one or more individual SMBHBs by the end of the decade

Individual SMBHB Sources

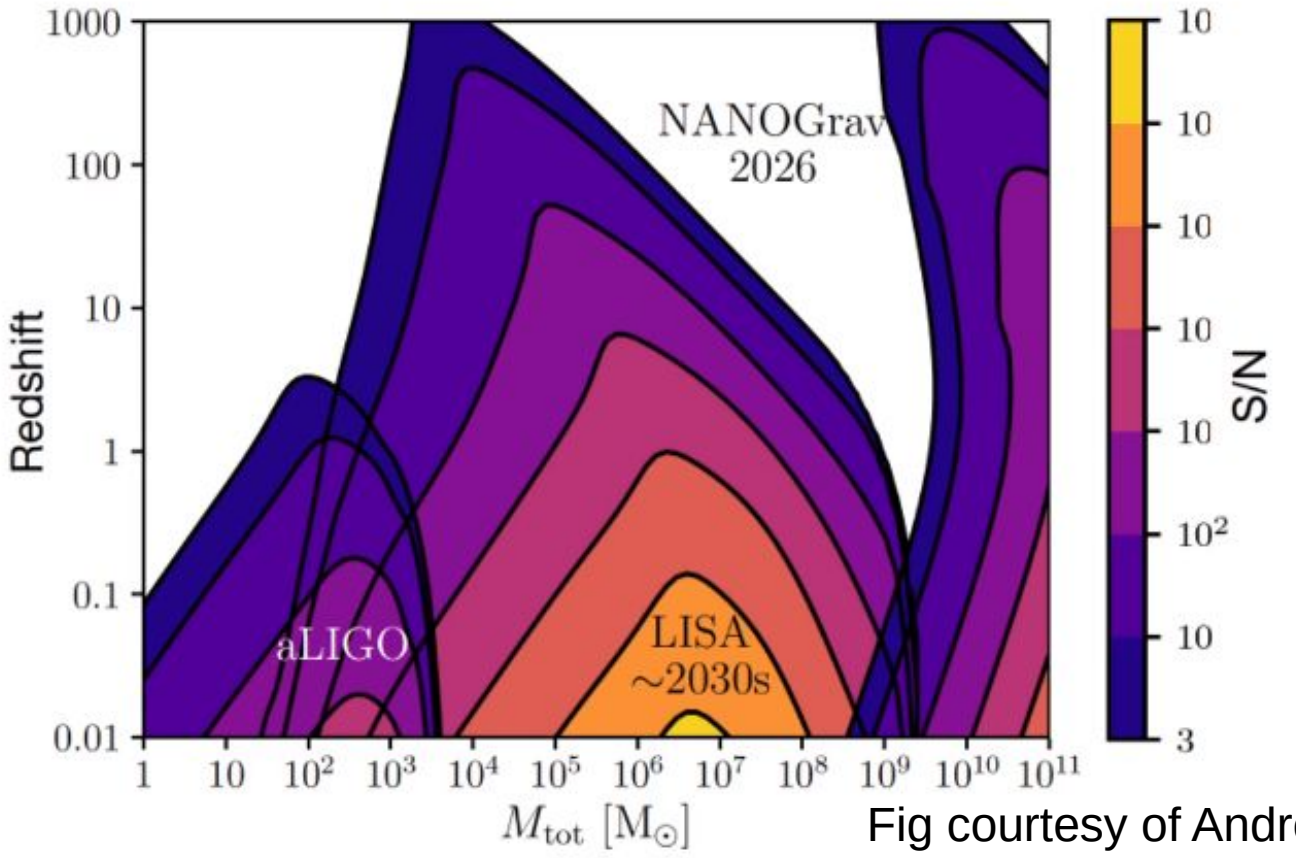
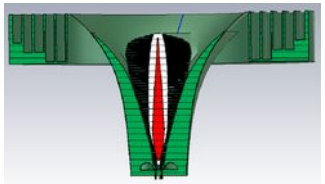


Fig courtesy of Andrew Kaiser

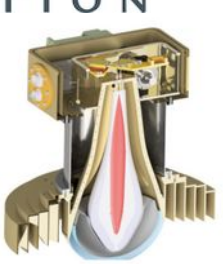
Wideband Receiver for GBT

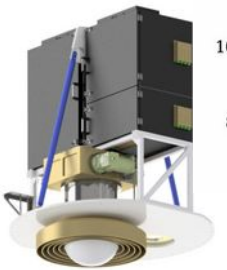
- **Need multi-frequencies for ISM removal**
  - Current systems have <800 MHz BW
  - **Ultra-wideband system** would give 2x better timing, fewer systematics, and more protection from scintillation
- Building a 0.7-4 GHz receiver for GBT, funded by Moore Foundation

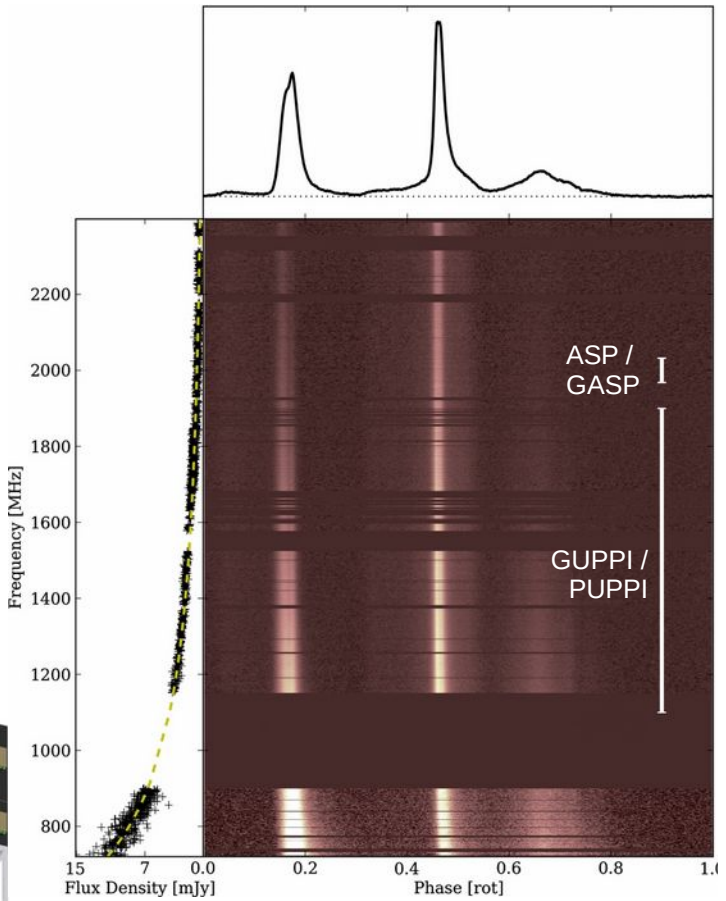


GORDON AND BETTY MOORE FOUNDATION

Hobbs et al. 2019, PASA, in press







Pennucci et al. 2014, ApJ, 790, 93

Summary

- NANOGrav is doing great and we are optimistic
- **Arecibo loss is terrible. Will slow, not stop progress.**
  - In long term, we need a replacement (e.g. DSA-2000)
- We have 15+ years of data in hand
- Our work with IPTA will make things even better
- Data are intriguing and we expect a detection within the next couple years
- In the meantime, tons of other science (e.g. Cromartie et al. 2019 massive NS)